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THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

EFFECT OF SACK DIMENSIONS ON IMPACT BEHAVIOR

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A Progress Report

to

MULTIWALL SHIPPING SACK PAPER MANUFACTURERS

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EFFECT OF SACK DIMENSIONS ON IMPACT BEHAVIOR

SUMMARY

An exploratory study was conducted to determine the effect of sack dimensions on the impact behavior of a sack. Two-ply sacks were handmade from samples of regular and extensible paper in the conventional construction of the standard pasted valve cement sack, except that (a) the length and width dimensions were varied (at constant volume) and (b) the sacks were of less than standard volume. The length-to-width ratios ($\underline{L}/\underline{W}$) ranged from 2.09 to 0.35. (The standard cement sack has $\underline{L}/\underline{W}$ = 1.27.) The experimental sacks were filled with cement and evaluated in progressive height face impact.

The long, narrow sacks failed predominantly in a lengthwise "tear" on the face; this pattern of failure suggests cross-direction tension rupture. Increasing the width of the sack decreased the number of such cross-direction tension failures. This trend may be explained as follows: while the energy absorption capacity per unit area of the paper remains constant, the increase in sack width decreases the induced energy per unit area in the cross direction of the paper; for sufficiently short, wide sacks, cross-direction rupture does not occur.

It was anticipated that short, wide sacks would fail predominantly in <u>machine</u>-direction tension on the face. This did not occur within the range of configurations of this study. Instead the rupture was predominantly at the corners of the sack, indicating that the corner areas were the next weaker areas of the sack once cross-direction rupture in the face was inhibited by varying the sack dimensions.

Sack performance (safe inches of drop) varied markedly with length-to-width ratio. Three of the four samples of paper exhibited maximum performance when the face of the filled sack was approximately square. This maximum performance was 3-1/2 to 4 times that of the long, narrow sacks and 1-1/3 to 2-1/2 times that of short, wide sacks.

The effect of sack dimensions on performance and nature of failure indicates that it is possible to select sack dimensions so as to give maximum performance from a paper with given directional properties. Conversely, within practical limits, it should be possible to tailor the directional properties of paper to give maximum performance for a given size sack. In principle this involves adjusting the ratio of strengths in the two principal directions of the paper to match the ratio of induced "stress" in the two directions. It would appear that extensible papers may offer greater latitude than flat kraft papers in applying the concept.

The importance of sack dimensions to sack performance may also be viewed as the importance of the stresses induced in the sack during impact (as contrasted with paper strength). Dimensions, along with commodity and drop test parameters, determine the induced stresses which in turn determine when a sack fabricated from a given paper will fail. Work is in progress to gain a better understanding of the stresses induced in a sack during impact, through measurement of the pressure exerted by the commodity and the strain induced in the sack paper.

INTRODUCTION

In the analysis of the performance of the pasted valve cement sacks of the first and second fabrication programs (1, 2) it has not been necessary to be concerned directly with the stresses applied to the sack by its contents — rather only with the material strength of the sack paper. This situation existed because all of the sacks were constructed to the same design and dimensions, filled with the same type and amount of commodity and subjected to the same impact tests. Thus, it was appropriate to assume that to a first approximation all of the sacks were subjected to the same magnitude of stresses (in the generalized sense of the word) — at least within the regular papers and within the extensible papers.

From those studies there have resulted a number of correlation equations relating sack performance to various paper properties under given conditions of impact (1, 2). The empirical constants in these equations may be thought of as reflecting the particular sack construction and commodity employed in those studies. It may be expected that a generalized equation would embrace factors representing commodity and sack construction — factors which reduce to the aforementioned empirical constants for the particular conditions existing in the first and second fabrication programs. Thus, the equations containing only paper strength properties may be looked upon as a first step in the development of more general equations describing sack performance.

From considerations such as these it was decided to undertake an exploratory study of the effect of sack dimensions on the impact performance of the sack. As a starting point for discussion of this study, it may be noted that a large number of the sacks from the second fabrication program failed in a lengthwise "tear" on the sack face when repeatedly impacted in progressive height face drop (3). This failure is illustrated by the jagged line in Fig. 1 and is apparently a cross-direction tension failure.

One elementary way of explaining the orientation of the failure line in Fig. 1 is by consideration of a one-inch wide strip AA' of paper in the cross direction across the face of the sack, as illustrated in Fig. 2. The "explosion" of the contents against the sides of the sack imparts a given amount of energy (per inch of width) which must be absorbed by the strip AA' along its length. A similar statement may be made regarding the strip BB' oriented in the machine direction of the paper. Arguing from the active mass concept of commodity behavior (4), it may be assumed that the total impact energy is the same for both strips. For a conventional cement sack, therefore, it follows that the energy absorbed per unit length of the strip AA' is greater than in strip BB' because the width of the sack is less than the length. Cross-direction failure apparently occurs because the induced energy per unit area in strip AA' exceeds the energy absorption capacity per unit area in the cross direction of the paper before the induced energy in strip BB' exceeds the machine-direction energy absorption capacity. It is believed that after the first impact the available energy absorption capacity in either direction of the paper is less than the virgin energy because of the nonrecoverable energy removed from the paper by the preceding drops.

The above considerations suggest that it may be possible to decrease the length dimension of a sack relative to the width dimension to a degree where the induced energy in the M.D. strip BB' exceeds the available energy absorption capacity in that direction before the C.D. energy absorption capacity is exceeded in strip AA'. That is, the sack would suffer a machine-direction tension failure and the rupture line would be perpendicular to that shown in Fig. 1.

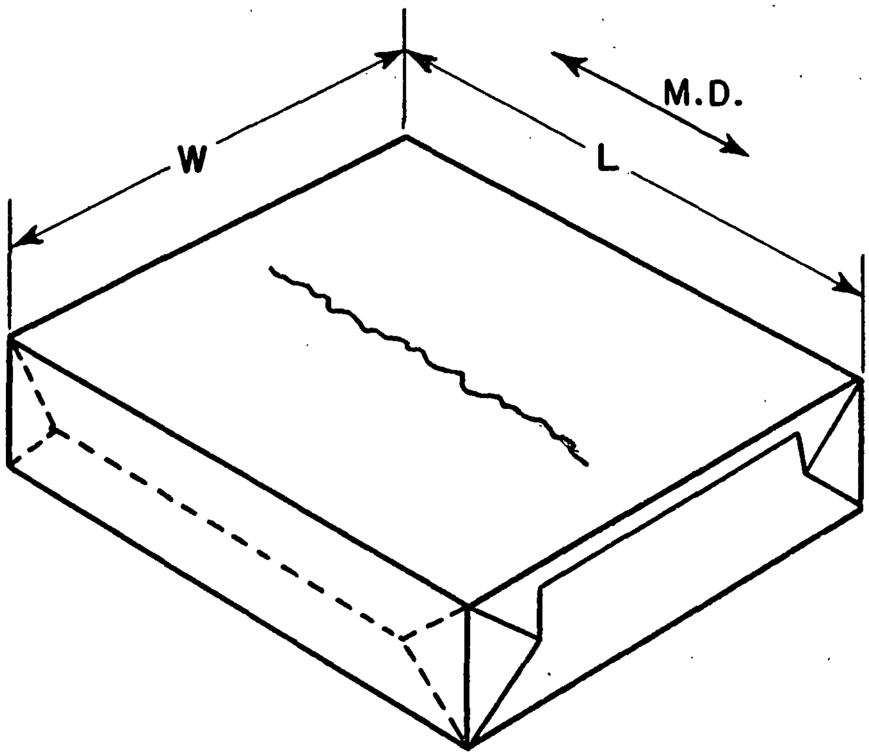

Figure ~~1~~ 9. Typical Impact Failure in a Multiwall Sack

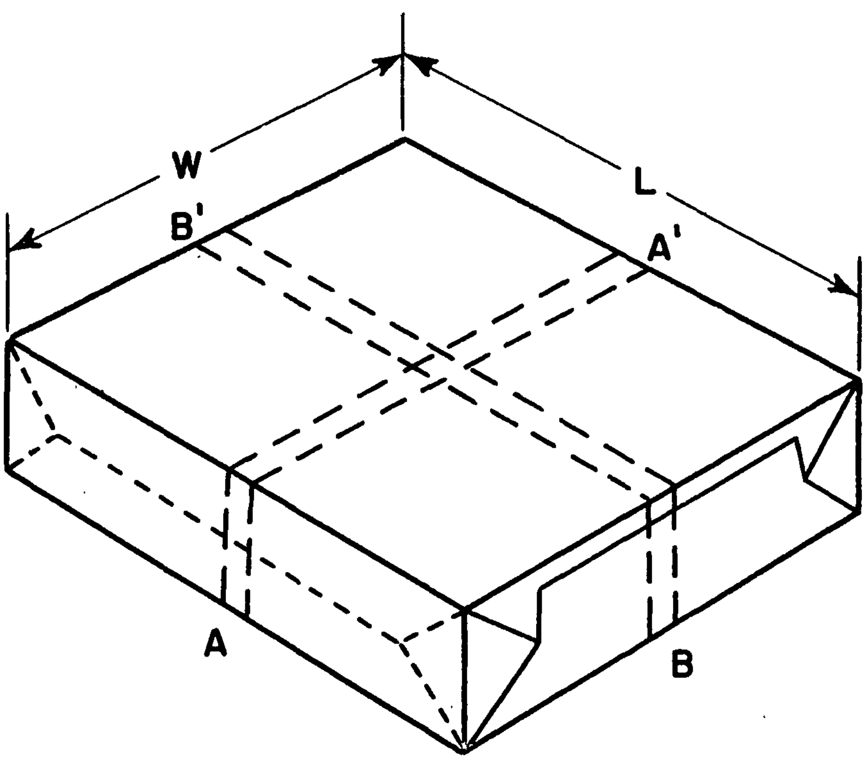

Figure ~~2~~ 10. Strip Concept of Applied Energy in Sack Face

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The practical importance of the speculated reversal of failure is as follows: At some dimensional configuration intermediate between those discussed above, failure in both machine-direction tension and cross-direction tension of a given paper should be equally likely. In terms of the elementary analysis given above, this would occur if the length-to-width ratio of the sack equals the ratio of cross-machine to machine-direction energy absorption capacities (per unit area) on the drop causing rupture. [This is only approximate because it neglects (a) the effect of bag depth on strip length, (b) nonuniformity of induced energy along a strip, and (c) biaxial strength effects.] This situation of equally likely failure would represent the best utilization of the strength of the sack paper in both directions, because at other dimensional configurations the strength in the direction which does not fail is not being fully exploited.

This reasoning suggests that it may be possible to select sack dimensions on the basis of improved utilization of the strength in both directions of a given sack paper. Or conversely, for given sack dimensions (determined, for example, by trade specifications and practices or conversion and handling considerations) it may be possible to specify the relative magnitudes of strength in the two directions so that neither direction of the paper is overstrength, relative to the other. It may be expected that, in general, economic advantage would derive from production of sack paper whose directional properties are appropriately balanced to the sack dimensions, or sack dimensions to paper properties.

To explore the area of dimension effects a number of two-ply sacks with various ratios of length-to-width were made from regular and extensible sack papers and evaluated in progressive height face impact. The nature of failure and the level of performance of the sacks were studied with regard to the effect of length-to-width ratio.

MATERIALS

The experimental sacks were fabricated from one sample of 50-lb. regular kraft sack paper and three samples of 50-lb. extensible kraft sack paper from the second fabrication program, as listed below:

Sample	Description
Run JJ	regular
Run MM	6% extensible
Run VV	9% extensible
Run OO	12% extensible

TEST PROCEDURE

All materials were subjected to standard conditioning at 50% R.H. and 73°F. before fabrication and testing of the sacks.

Two-ply sacks were made by hand with length and width dimensions given in Table I. Length and width are defined in terms of the sketch in Fig. 3, where it may be seen that tube width is used. Except for dimensions and number of plies, the sacks were of the same construction as the pasted valve cement sacks of the second fabrication program. In the case of the wide sacks of configuration E, it was necessary to make a pasted seam at the center of both face and back of the sack because the parent roll width was only 38 inches.

The standard cement sack has the following dimensions, approximately: $\underline{L}$ = 23-3/8 in., $\underline{W}$ = 18-3/8 in., $\underline{L}/\underline{W}$ = 1.27. The dimensions of the experimental sacks were selected so that the volume (and hence the total weight of the contents) was approximately constant for all configurations. Volume was calculated on the basis that the sacks are rectangular parallelepipeds of constant depth, of length as defined in Fig. 3, and of width equal to the tube width minus 3.4 inches.

TABLE I

SACK DIMENSIONS

Configuration	Dimensions of Experimental Sacks		
	Length, L, in.	Width, W, in.[a]	L/W
A	23.2	11.1	2.09
B	16.5	14.2	1.16
C	13.4	16.8	0.80
D	12.0	18.4	0.65
E	8.5	24.3	0.35

[a]Tube width.

Ten sacks of each configuration were made from each of the four samples of paper, with the exceptions that (a) configuration A was made only for the regular and the 9% extensible papers (Runs JJ and VV, respectively), and (b) configuration E was not made from the 9% extensible paper because the supply was exhausted.

In addition to the sacks described above, paper from Runs JJ and VV was fabricated into cross-grain sacks in configurations B and D. That is, the machine direction of the paper was parallel to the width dimension of the sack.

The sacks were filled with 43 lb. of cement and evaluated in the progressive height face drop test starting at 24 inches and progressing in 6-inch increments of drop height.

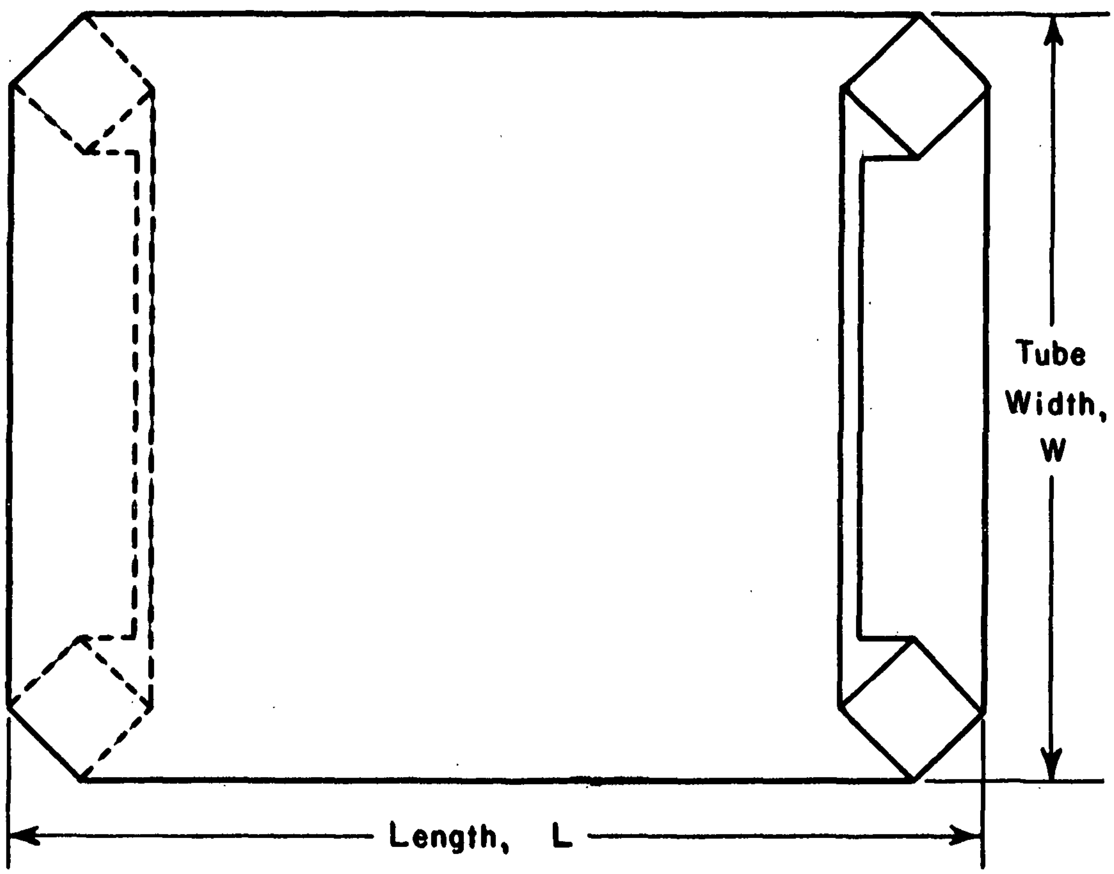

Figure 3. Sack Dimensions

DISCUSSION OF RESULTS

Experimental two-ply sacks were fabricated with various ratios of length-to-width (constant volume), filled with cement and evaluated with respect to progressive height face impact performance and nature of failure.

NORMAL GRAIN SACKS

The average performance of the normal grain sacks is shown in Table II. Each entry is the average number of safe inches in progressive height face drop from ten sacks of a given paper and configuration.

TABLE II

PERFORMANCE OF EXPERIMENTAL SACKS IN PROGRESSIVE HEIGHT FACE IMPACT

Configuration	Dimensions			Safe Inches			
	L	W	L/W	Run JJ (Regular)	Run MM (6% Ext.)	Run VV (9% Ext.)	Run OO (12% Ext.)
A	23.2	11.1	2.09	96	--	164	--
B	16.5	14.2	1.16	213	272	326	402
C	13.4	16.8	0.80	338	347[a]	660	516
D	12.0	18.4	0.65	258	386[a]	527	410
E	8.5	24.3	0.35	135	289	--	580

[a]Average from nine sacks.

Sketches of the several sack configurations are given in Fig. 4, 5, 6, and 7. These illustrations show the sack dimensions, the ratio of length to width (tube width), the number of safe inches, and the location of sack rupture. The numeral appended to each rupture line denotes the number of sacks which exhibited

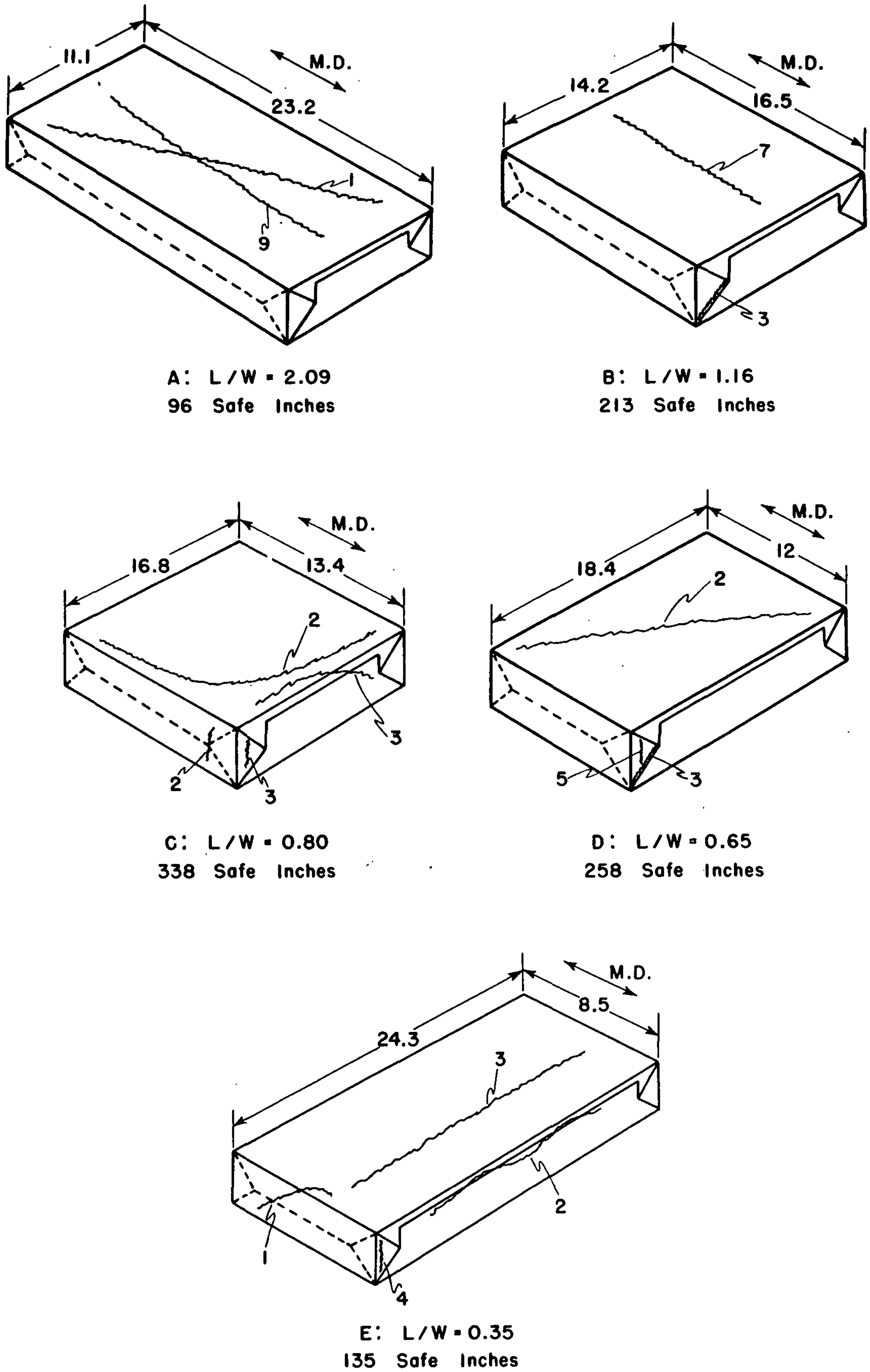

Figure ~~4~~ 12. Failure Patterns in Regular Kraft Sacks (Run JJ) of Various Configurations (Normal Grain)

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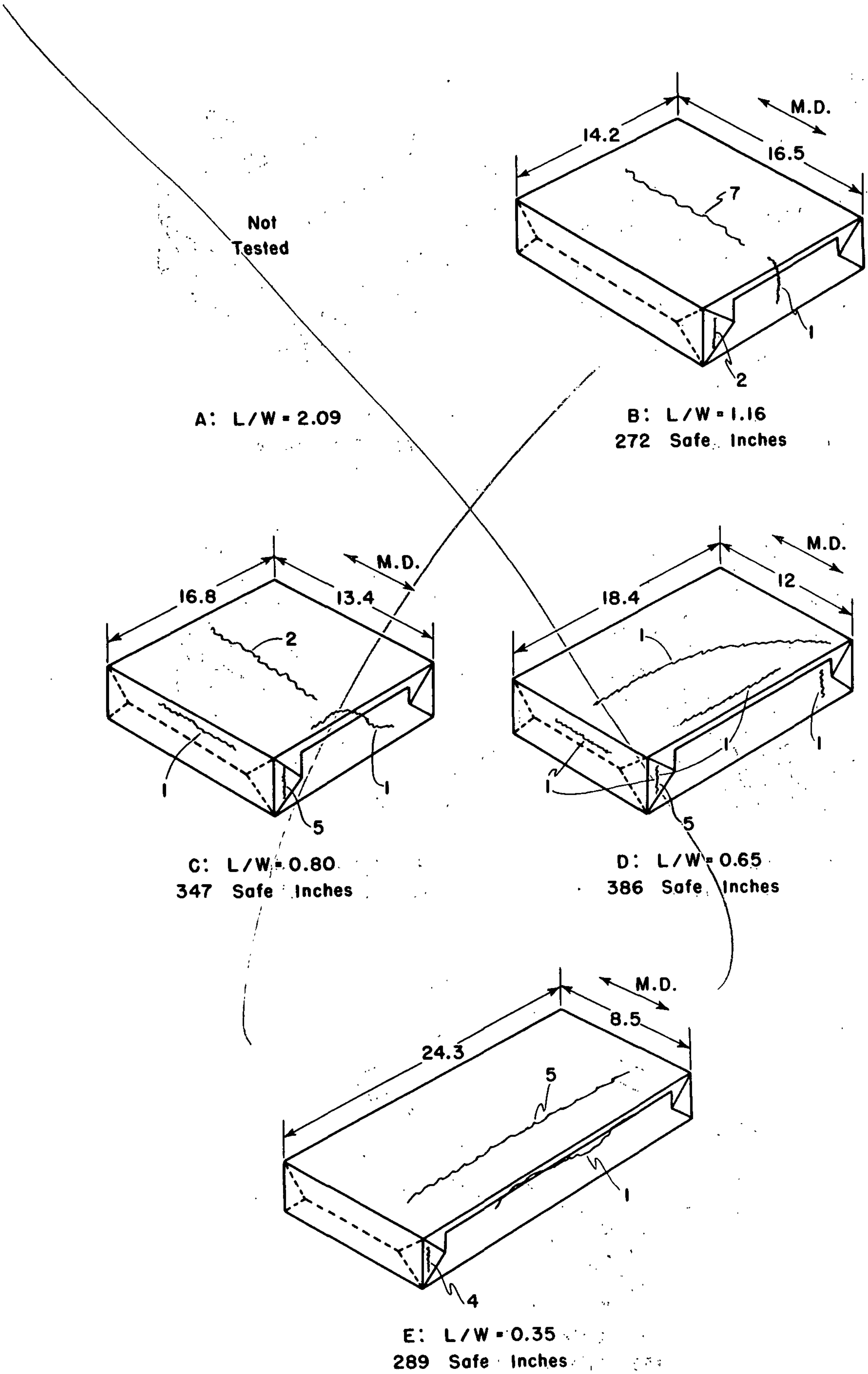
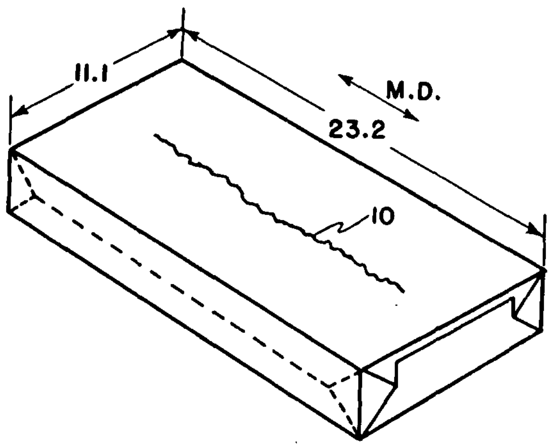
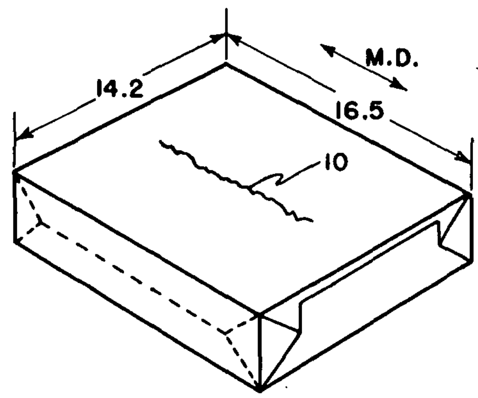


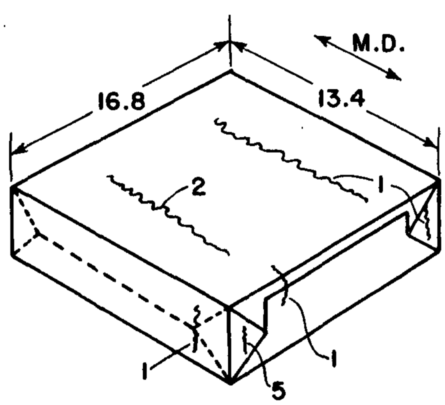
Figure 5. Failure Patterns in 6% Extensible Kraft Sacks (Run MM) of Various Configurations (Normal Grain)



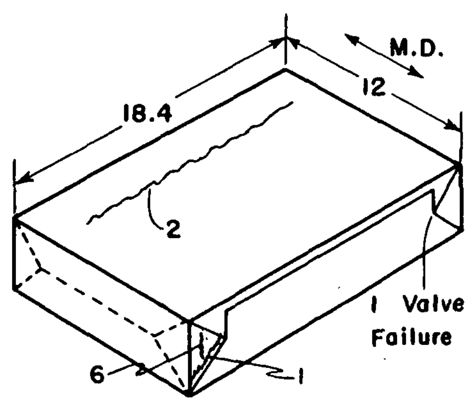
A: L/W = 2.09
164 Safe Inches



B: L/W = 1.16
326 Safe Inches



C: L/W = 0.80
660 Safe Inches



D: L/W = 0.65
527 Safe Inches

Not
Tested

E: L/W = 0.35

Figure 6. Failure Patterns in 9% Extensible Kraft Sacks (Run VV) of Various Configurations (Normal Grain)

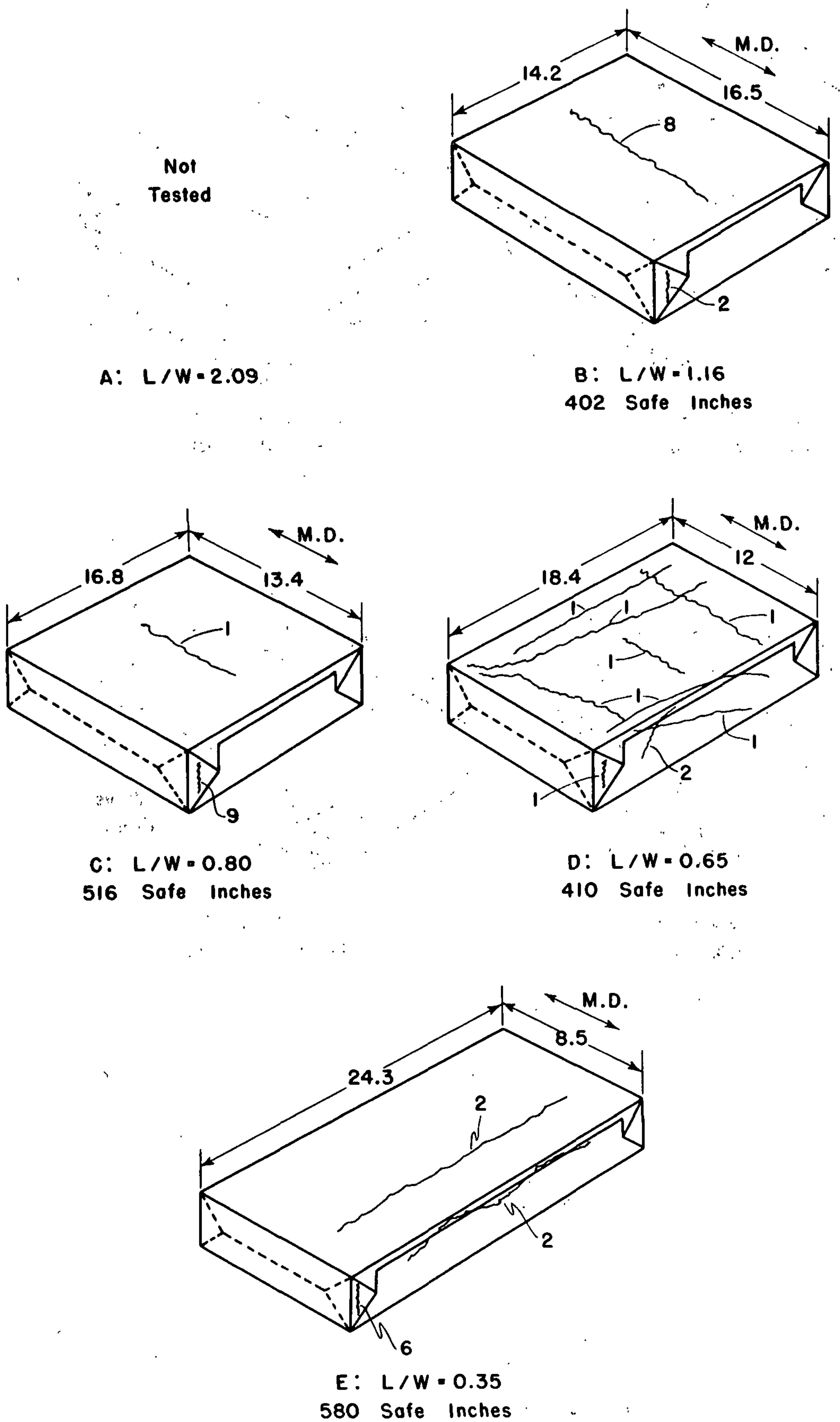


Figure 7. Failure Patterns in 12% Extensible Kraft Sacks (Run 00) of Various Configurations (Normal Grain)

that mode of rupture. Each of Fig. 4, 5, 6, and 7 pertains to one sample of paper.

With the regular sacks (Run JJ), for example, it may be seen in Fig. 4 that the long, narrow sack (configuration A, L/W = 2.09) experienced a high frequency of what appears to be cross-direction tensile rupture on the face of the sack (that is, a lengthwise tear). In nine of the ten sacks, the rupture line was parallel to the machine direction of the paper; the one remaining sack failed along the diagonal of the face. These locations of failure appear to be compatible with the elementary explanation given in the Introduction, namely, that the small width dimension gives rise to high levels of induced energy in the cross-machine direction.

Configuration B is a length-to-width ratio of 1.16 and is reasonably near to the ratio of a conventional cement sack, namely, 1.27. Seven of the ten experimental sacks failed in a lengthwise tear (apparently cross-direction tensile rupture) while three sacks failed in the diamond area at a corner.

It may be of interest to note that the average safe inches more than doubled in proceeding from the long, narrow sack to the more conventional configuration, namely, 96 to 213 safe inches. In particular, the nine sacks failing in cross-direction tension on the face for configuration A exhibited an average performance of 92 safe inches, whereas the seven sacks of configuration B that failed in the face had an average performance of 201 safe inches. In physical terms the behavior of these two sack configurations may be described as follows: the kinetic energy of the system of sack and contents is the same for both configurations A and B when dropped from the same height. The amount of active mass impinging on the elemental strip AA' (see Fig. 2) is the same for both configurations and hence the kinetic energy applied to the strip is the same in both cases. The elemental strip in configuration B is substantially longer than in configuration A, however, so that the energy induced per square inch of the strip is, on the average, smaller in configuration B than in A. Inasmuch as the capacity of the paper to absorb energy (per square inch) is the same in both sack configurations, it is understandable that a greater number of drops are sustained with configuration B than A before the induced energy exceeds the available energy absorption of the paper.

Sack configuration C had $L/W = 0.80$, that is, the length was less than the width. Note that the top (or bottom) of this unconventional sack is oriented pictorially the same as the other sacks in Fig. 4. In plan view, the face of the filled sack of these dimensions appears to be virtually square. This sack configuration exhibited a variety of postfailure patterns. Five of the sacks failed in the diamond in what appears to be machine-direction tensile failure; three were more or less along an end crease and seemingly machine-direction tensile rupture; and two sacks exhibited sweeping failure around the face, not uniquely associated with either direction of the paper. A further substantial increase in safe inches was experienced at this reduced L/W ratio, namely, from 213 to 338 safe inches.

The progressive increase in performance in progressing from configuration A to C may be explained as follows: As discussed above, although the applied energy at the sidewall remains constant, increasing the length of the elemental strip in the cross direction diminishes the induced energy per square inch of the strip, thereby delaying cross-direction tension failure in the strip until some greater number of drops have occurred. In contrast, the change in length-to-width ratio probably has little or no effect upon the induced energy in the paper at the corners of the sack inasmuch as the active mass and the quantity of paper which can absorb energy at the corners can be expected to remain appreciably unaffected by length and width dimensions of the sack. Under these conditions of diminishing induced energy in the face strip and constant induced energy in the paper at the corners, it is understandable that rupture may occur first at the corner when the sack width is made sufficiently wide as in configuration C because now the corner areas become the critical regions of the sack. Moreover, more drops are required to reach this point than were necessary to cause face failure in the narrower sacks of configuration A or B.

In configuration D ($\underline{L}/\underline{W}$ = 0.65) eight of the regular sacks failed in the diamond and two in a diagonal tear on the face. The safe inches for this configuration was 258, a decrease from the previous case.

In configuration E ($\underline{L}/\underline{W}$ = 0.35) four of the sacks failed in the diamond area, two at an end, one on the side and three across the face — the latter in what appears to be machine-direction tension failure. It should be mentioned that, while only three of these sacks are illustrated as failing on a face, four of the remaining sacks suffered premature failure in the outer ply of the face (machine-direction tension) but withstood additional impacts and subsequently failed at the corner, end, or side of the sack. The safe inches of drop was 135, a further decrease.

Considering the progression from configuration A to E for Run JJ, it appears that it was indeed possible to inhibit cross-direction tensile rupture by increasing the width dimension. The number of definite cross-direction ruptures on the face in this succession were 9, 7, 0, 0, and 0 for configurations A through E (out of ten sacks at each configuration).

It was anticipated that this progression of sack dimensions would exhibit a reversal from cross-direction to machine-direction rupture on the face of the sack. This did not occur, however, in a clear-cut fashion. While cross-direction rupture was inhibited at the three lowest L/W ratios (C, D, and E), the majority of failures in these sacks was in the diamond areas at the corner of the sack or in other regions of the sack such that failure could not be associated uniquely with either the machine or cross direction. Only three sacks in each of configurations C and E ruptured in the machine-direction mode on the face of the sack. Apparently, the corner is a zone of relatively high stress in the sack. Diminishing the cross-direction stresses by increasing the sack width prevented cross-direction rupture, but rather than fully reversing the rupture to machine-direction face failure, the rupture in general shifted to the corner of the sack.

As mentioned above, the performance of the sacks varied with length-to-width ratio. This behavior is illustrated in the graph of Fig. 8 which shows the performance of Run JJ at each configuration. It may be seen that by decreasing the length-to-width ratio (from configuration A to E) sack performance increased to a maximum at configuration C and then decreased at the lower ratios. The highest performance occurred at L/W = 0.80 which is essentially a square sack when filled with commodity. The maximum performance is 3.5 times that of the long, narrow sack (L/W = 2.09) and 2.5 times that of the short, wide sack (L/W = 0.35). Figure 8 also shows a limit band within which the true values of performance can be expected to lie with 95% confidence. The width of this band in the vertical direction reflects the variability within each sample of ten sacks and indicates the uncertainty in the observed average safe inches (assuming normal curve statistics). It may be seen that it is not possible to construct either a horizontal line or a curve without a maximum within the confines of the limit band. Thus, beyond reasonable doubt, the performance of these sacks exhibits a maximum at a length-to-width ratio in the neighborhood of 0.80.

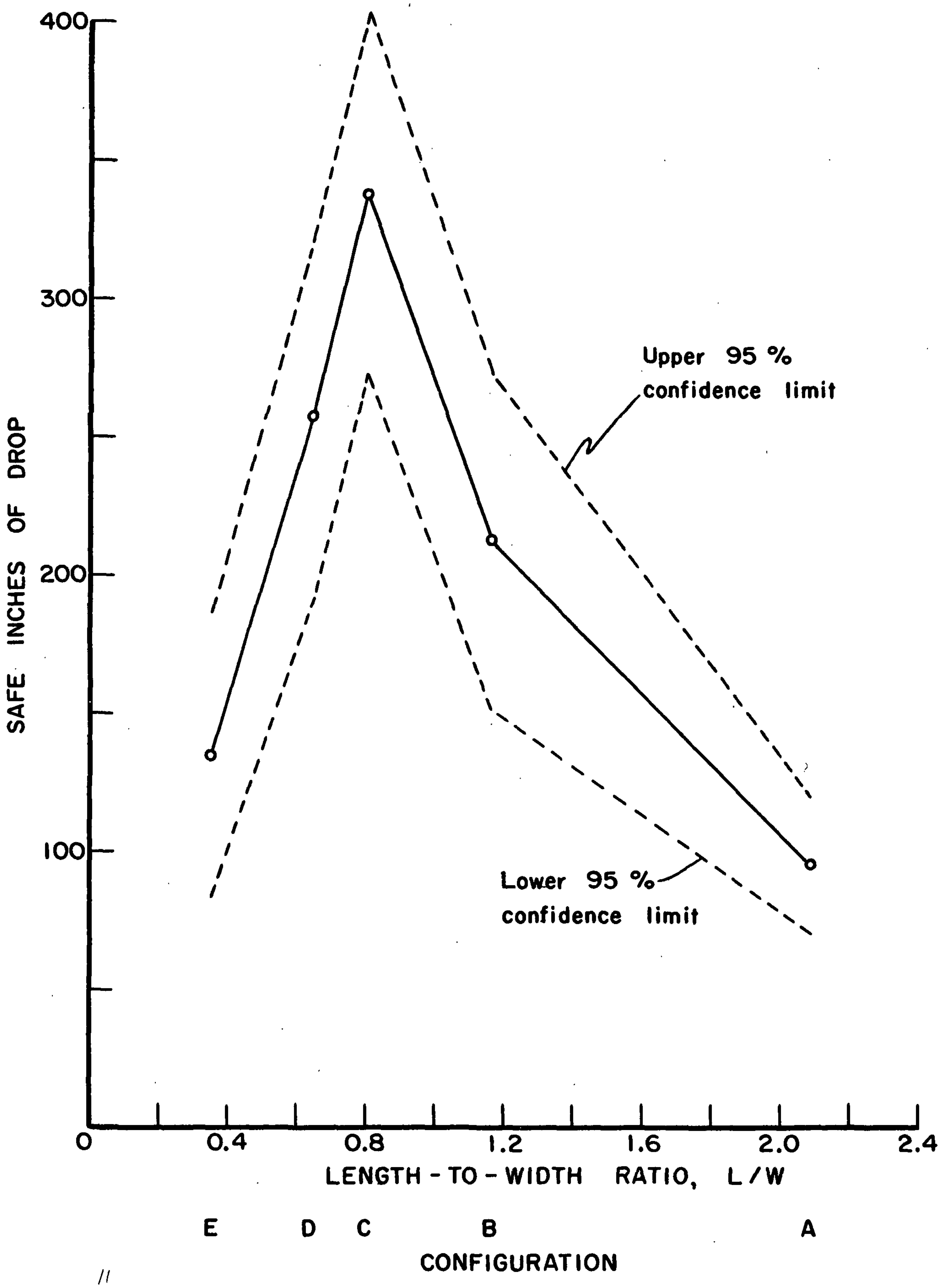


Figure 11. Effect of Length-to-Width Ratio on Progressive Height Impact Performance of Regular Sacks (Run JJ) (Normal Grain)

In summary for Run JJ (a regular kraft sack paper), it was found that the nature of impact rupture of the sack depended on the dimension ratio of the sack. Increasing the width dimension inhibited the cross-direction tension failure which was common in long, narrow sacks. However, the increase in width dimension did not lead completely to the anticipated machine-direction rupture on the face of the sack. Instead, the sacks failed predominantly at a corner in the diamond area, which apparently is the next source of "weakness" in the sack once cross-direction rupture is prevented. It was found that the performance of the sacks in terms of safe inches also varied with length-to-width ratio. Increasing the width dimension relative to the length increased the impact performance markedly. Maximum performance occurred with an approximately square sack. Further increase in width relative to the length resulted in a decrease in performance.

Returning to Fig. 5, 6, and 7, it may be seen that sacks fabricated from the three samples of extensible paper behaved in many ways similar to the regular kraft sacks described above. In general, for L/W greater than unity, the predominant type of failure was cross-direction tension on the face of the sack. Increasing the width markedly reduced the frequency of cross-direction rupture and most of the failures occurred near the corner of the sack. With short, wide sacks (low L/W ratio), a number of machine-direction tension failures occurred on the face of the sack.

These trends may be visualized in terms of the data in Table III which summarizes the type of failure (machine or cross machine) of all the sacks of this study. For this purpose, the classification "machine direction" refers to what appears to be machine-direction tension failure in the face or sidewalls of the sack but not including the failures at the corner or in the ends of the sack (similarly for "cross direction"). No attempt was made to classify failure in

TABLE III

NATURE OF PAPER RUPTURE IN EXPERIMENTAL SACKS

			Number of Sacks Exhibiting:		
Sample	Configuration	L/W	Machine-Direction Tension Rupture	Cross-Direction Tension Rupture	Other
JJ (Regular)	A	2.09	0	9 (92)[a]	1 (132)
	B	1.16	0	7 (201)	3 (242)
	C	0.80	3 (362)	0	7 (328)
	D	0.65	0	0	10 (258)
	E	0.35	3 (116)	0	7 (143)[b]
MM (6% Extensible)	A	2.09	--	--	--
	B	1.16	0	7 (240)	3 (346)
	C	0.80	1 (234)	3 (258)	5 (423)
	D	0.65	1 (234)	0	8 (405)
	E	0.35	5 (224)	0	5 (353)[c]
VV (9% Extensible)	A	2.09	0	10 (164)	0
	B	1.16	0	10 (326)	0
	C	0.80	0	2 (558)	8 (686)
	D	0.65	2 (510)	0	8 (531)
	E	0.35	--	--	--
OO (12% Extensible)	A	2.09	--	--	--
	B	1.16	0	8 (402)	2 (396)
	C	0.80	0	1 (180)	9 (553)
	D	0.65	2 (402)	2 (510)	5 (408)
	E	0.35	2 (597)	0	8 (575)[b]

[a] Numeral in parentheses denotes average safe inches.

[b] Four sacks suffered premature M.D. tension failure in outer ply on face.

[c] Two sacks suffered premature M.D. tension failure in outer ply on face.

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these latter locations according to direction because it is believed the ruptures are more a result of converting and sack design (stress concentration at creases and folds, etc.) than parent paper properties. These failures have been listed as "Other" in Table III; this classification also includes several face failures which cannot be described as solely machine- or cross-direction ruptures.

Table III reveals that, for extensible sacks as well as regular sacks, there was predominantly cross-direction tension failure at the higher $\underline{L}/\underline{W}$ ratios, say, at ratios greater than unity. On the other hand, at low $\underline{L}/\underline{W}$ ratios (short, wide sacks) the incidence of cross-direction ruptures was reduced to three or less out of ten; a number of machine-direction ruptures occurred although most of the failures were near a corner of the sack (or at least could not be uniquely classified as machine- or cross-machine rupture). Thus, the summary statements given above for regular paper also apply in general to the extensible sacks of this study.

The numeral in parentheses adjacent to each nonzero entry in Table III denotes the average safe inches for the sacks concerned. For example, with $\underline{L}/\underline{W}$ = 1.16 of Run JJ, seven sacks failed in cross-direction rupture at an average performance of 201 safe inches; three sacks failed at a corner and the average safe inches was 242. In six out of eight comparisons of this type which can be made in Table III, the safe inches corresponding to cross-direction tension failure in the face was lower than the safe inches for the classification "Other" which is primarily corner failures. This observation is in keeping with the general trend of the entire experiment, namely, increasing the width dimension of the sack decreases the frequency of cross-direction tension failures and failure shifts to the corner of the sack, accompanied by an increase in the level of performance.

Similarly, in six out of eight comparisons, the level of performance of sacks exhibiting machine-direction tension failure on the face was lower than for sacks which failed elsewhere — primarily at the corner. Thus, corner failures apparently correspond to a higher level of performance, in general, than either machine- or cross-direction failures on the face of the sack for the specimens of this study.

The impact performance in terms of safe inches of the extensible sacks as a function of length-to-width ratio is shown graphically in Fig. 9 (the regular Sample JJ discussed above is included for reference). The performance of Run MM (6% extensible) and Run VV (9% extensible) as a function of $\underline{L}/\underline{W}$ follow a trend paralleling the regular paper JJ — that is, maximum performance at intermediate length-to-width ratios. In the case of Run VV, the performance at $\underline{L}/\underline{W} = 0.80$ is four times that of $\underline{L}/\underline{W} = 2.09$. The behavior of Run OO (12% extensible) is less clear. Maximum performance was achieved at the lowest $\underline{L}/\underline{W}$ ratio, although a secondary maximum occurred at $\underline{L}/\underline{W} = 0.8$. The 95% limit band for Run OO is shown in Fig. 10. The width of the limit band is compatible with several hypotheses, for example, progressively increasing performance with decreasing $\underline{L}/\underline{W}$ ratio, or maximum performance at about $\underline{L}/\underline{W} = 0.65$. In view of the high machine-direction stretch of this paper (12%), it is possible that maximum performance occurs at a lower $\underline{L}/\underline{W}$ ratio than for the other samples of paper which have lower stretch.

The results of this study indicate that it is possible to select sack dimensions which will give maximum performance from paper of given directional properties. The converse of the above should also be possible, namely, that with practical limitations of papermaking it should be possible to tailor the directional properties of the paper to give improved performance from a sack of given dimensions. Considerably more technical understanding of sack impact behavior than is now available is required to specify how this may be accomplished in a specific case.

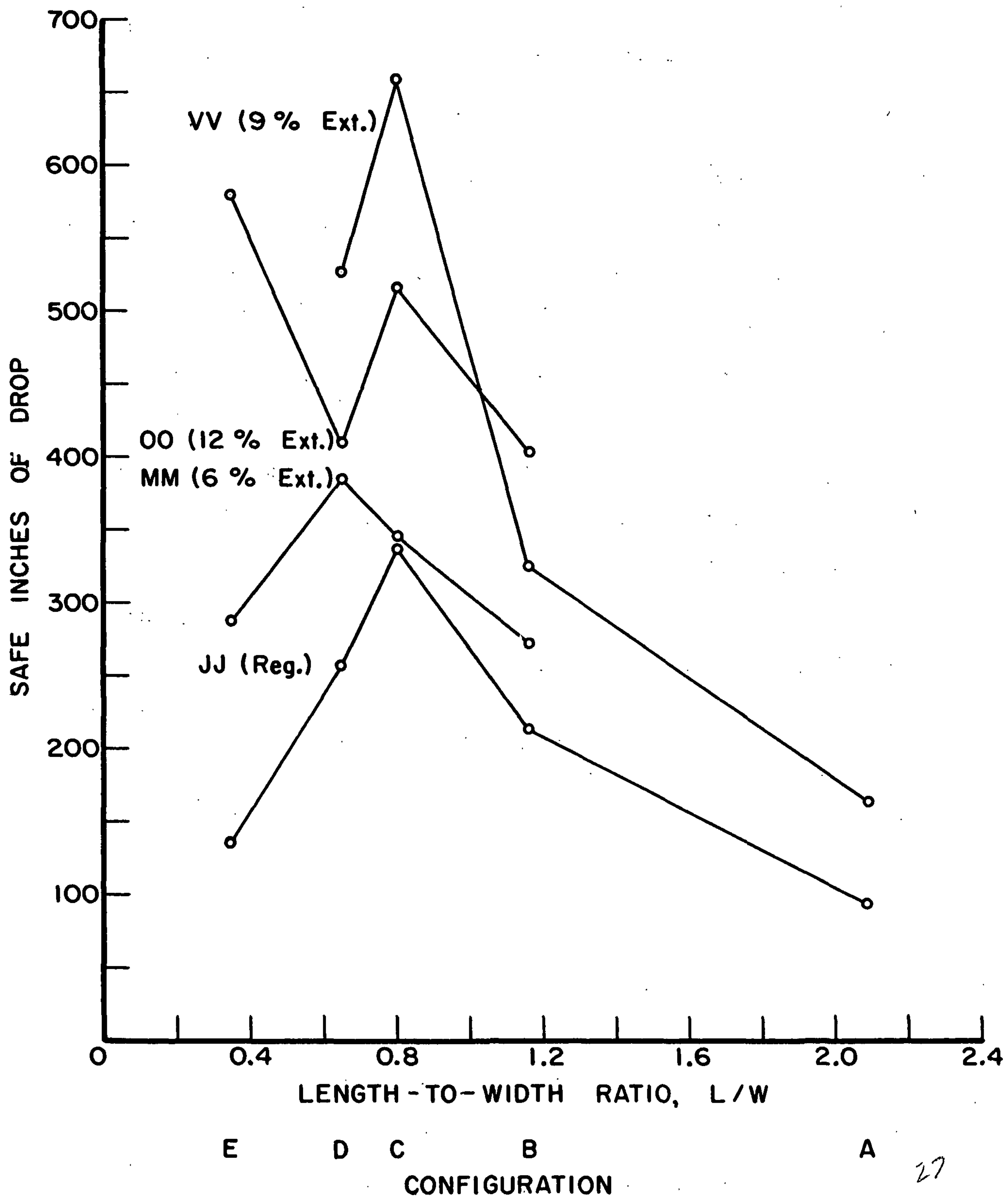

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Figure 9. Effect of Length-to-Width Ratio on Progressive Height Impact Performance of all Samples (Normal Grain)

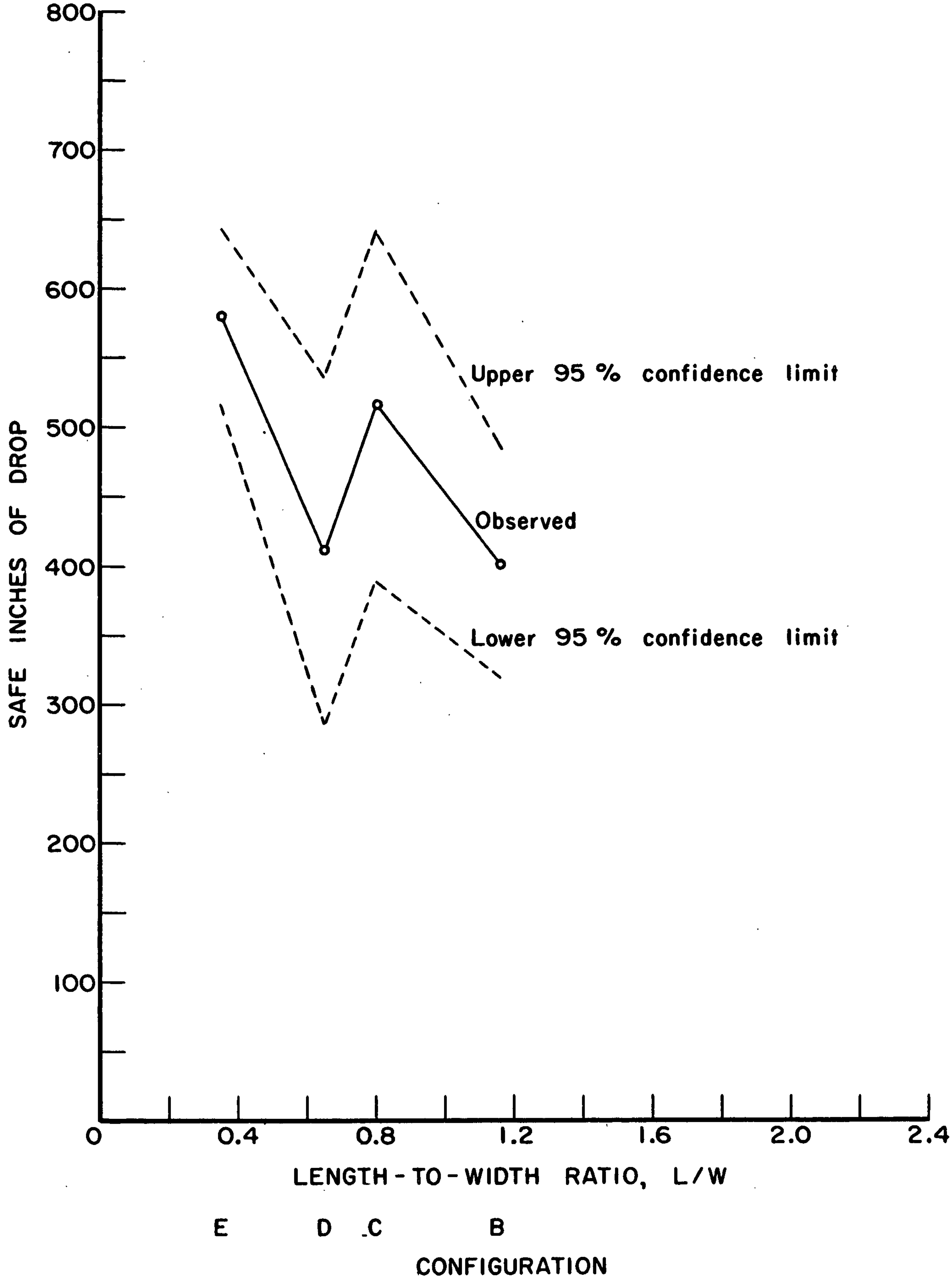

Figure 10. Effect of Length-to-Width Ratio on Progressive Height Impact Performance of Run 00 (12% Extensible) (Normal Grain)

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It may be of interest to note that the performance of the 12% extensible paper (Run OO) was inferior to that of the 9% extensible sample (Run VV) at two intermediate L/W ratios, 0.80 and 0.65. At L/W = 1.16 the two samples are ranked in the anticipated order in keeping with their degree of machine-direction extensibility. Indeed, all four samples are ranked in the expected order at L/W = 1.16, as shown below. This ratio is reasonably near the dimensional ratio of the conventional cement sack. A comparison of the performance of the four samples fabricated as cement sacks (5) and at the most nearly comparable ratio in this study is given in Table IV.

TABLE IV

COMPARISON OF PERFORMANCE OF STANDARD CEMENT SACK AND EXPERIMENTAL SACK

	Safe Inches			
	Run JJ	Run MM	Run VV	Run OO
Standard 3-ply cement sack, L/W = 1.27	487	855	1038	1144
Experimental sack of this study, L/W = 1.16	213	272	326	402

Thus, it is only at L/W = 0.80 and 0.65 that the experimental sacks of the 12% extensible paper (Run OO) perform at unexpectedly low levels. It is difficult to offer an explanation for their low performance. A comparison of several properties of the energy and fatigue types for Runs VV and OO is given in Table V.

It is seen that Run OO (12%) is inferior to Run VV (9%) in a number of cross-direction properties, but this disparity would be expected to influence sacks of high rather than low L/W because of the preponderance of cross-direction failures at high L/W. Thus, it is not clear why the 12% extensible performed poorer than the 9% extensible at the intermediate L/W ratios. missing

TABLE V

COMPARISON OF ENERGY AND FATIGUE PROPERTIES
OF RUNS VV AND OO

	Run VV 9% Extensible	Run OO 12% Extensible
Stretch, %		
M.D.	9.2	11.3
C.D.	5.2	4.3
T.E.A., in. lb./sq. in.		
M.D.	1.341	1.403
C.D.	0.656	0.656
Elastic T.E.A., in. lb./sq. in.		
M.D.	0.212	0.207
C.D.	0.081	0.104
Thwing-Albert impact fatigue, falls	74	63
Frag burst energy		
M.D.	833	876
C.D.	511	419
Impulse, mNs.		
M.D.	28.0	29.1
C.D.	10.8	10.5
Strain fatigue life		
M.D.	13.2	15.3
C.D.	7.0	5.3
Energy fatigue life		
M.D.	11.3	11.8
C.D.	7.0	6.8

CROSS-GRAIN SACKS

Cross-grain sacks were made from Run JJ (regular) and Run VV (9% extensible) paper in L/W ratios of 1.16 and 0.65. The machine direction of the paper is parallel to the width dimension in a cross-grain sack. The failure patterns and performance levels of these sacks are shown in Fig. 11. It may be

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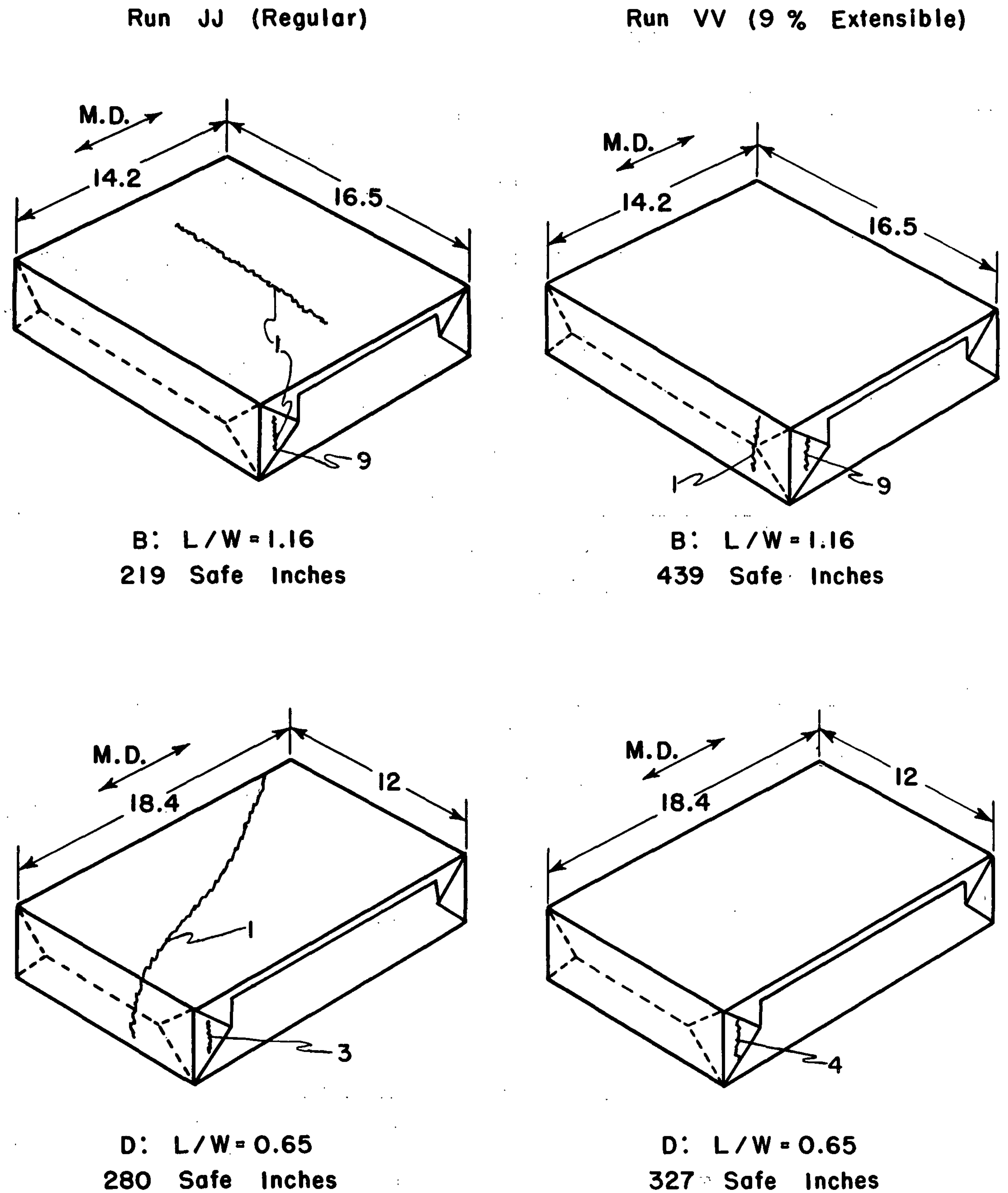

Figure 11. Failure Patterns in Cross-Grain Sacks

seen that, with few exceptions, these sacks (both regular and extensible) failed at a corner of the sack.

A point of possible interest arises in connection with the cross-grain regular sacks with L/W = 1.16 in Fig. 11. It may be recalled (see Fig. 4) that the normal grain sacks failed predominantly in cross-direction tension on the face. Speculation on the likely rupture pattern of the cross-grain sacks from consideration of virgin tensile energy absorption (T.E.A.) would probably anticipate a machine-direction tension failure on the face. This speculation derives from the observation that the machine-direction T.E.A. of Run JJ was 24% less than the cross-direction T.E.A. Thus, when the machine direction is aligned with the short dimension of the sack it might seem that the lower T.E.A. in this direction should virtually guarantee a tension failure in the machine direction of the face of the cross-grain sacks. This did not occur, but rather the rupture shifted to the diamond at the corner of the sack (except for one sack which failed in both the diamond and the face).

A possible explanation for the absence of face rupture in the seemingly weak machine direction lies in the following: The energy absorption capacity in the machine direction is less than in the cross direction only on the first several drops; repeated impacts deteriorate the available energies in the two directions at different rates, with the result, that after several drops, the relative strengths in the two directions are reversed and the machine direction is the stronger.

To illustrate this, repeated tension curves of Run JJ obtained with an Instron may be examined. Table VI lists the available energy (in arbitrary units of graph area) as a function of the number of load applications for each direction of the paper. [The applied energy in the Instron tests was progressively increased

1st line

from cycle to cycle as described in Reference (6) and was the same for both directions of paper; however, its relationship to impact energy is unknown.] The energy in the machine direction which was available to the first loading (that is, the virgin T.E.A.) was 24% less than the cross-direction energy, as noted above. The relative "strengths" in the two directions were in this same sense through the fifth application. On the sixth application, however, the strengths were reversed, with machine-direction available energy being about 5% higher than cross-direction energy. This difference increased with ensuing applications and on the eighth application, for example, the machine-direction energy was nearly 50% greater than the cross-direction energy. Viewed from this standpoint, it is perhaps understandable why the cross-grain face did not fail in machine-direction tension; that is, the machine direction was not the weaker direction of the paper at the time the sacks failed.

TABLE VI

AVAILABLE ENERGY IN MACHINE AND CROSS DIRECTION
IN REPEATED TENSION
(Run JJ)

No. of Load Application	Available Energy, units[a] Machine Direction	Cross Direction	Diff., %[b]
1	2523	3328	-24.2
2	2418	3092	-21.8
3	2350	2877	-18.3
4	2273	2618	-13.2
5	2176	2323	- 6.3
6	2075	1984	+ 4.6
7	1942	1601	+21.3
8	1810	1217	+48.7
9	1623	--	--
10	1518	--	--

[a]Arbitrary units of graph area.
[b]Based on cross direction.

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The above reasoning is not appropriate to the extensible sacks because, based on Instron repeated tension behavior of Run VV, the machine-direction available energy was initially about twice as great, and remained greater than, the cross-direction energy. In fact, the disparity increased with number of applications.

FUTURE WORK

This study was concerned with the effect of sack dimensions on impact performance and mode of rupture. Both were affected by variation in dimension ratios. It may be appreciated that, from a more general standpoint, variation in sack dimensions may be viewed as a variation of the stresses induced in the sack paper. Dimensions are one of three factors determining the impact stresses — the others being the commodity and the nature of the drop test (height, orientation, impact surface, etc.). Thus, the results of this study may be interpreted as showing the importance of the induced stresses that are developed in the impact test of a sack. Clearly, more than paper "strengths" are involved in sack performance. Strengths are important only in relation to the stresses acting in the paper.

For this reason, work is now going forward to gain a better understanding of the stresses set up in a sack by impact — with regard to type, magnitude, and distribution throughout the sack. Stress and energy in the paper *per se* are not directly measurable quantities and recourse must be had to measurement of other closely related quantities. Studies are now in progress relative to measuring (a) the pressures exerted on the interior of the sack (as a function of location, commodity, drop conditions, etc.) and (b) the strain induced in the sack paper as a result of impact.

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